SCDAP/RELAP5-3D©

An Advanced Computer Code for Reactor Accident Analysis

SCDAP/RELAP5-3D© is an advanced, state-of-the-art, best-estimate computer code[a] designed for simulating severe reactor accidents. The code predicts the thermal-hydraulic response of the reactor coolant system (RCS) and the progression of damage associated with reactor core and reactor vessel heatup. Links with other detailed, mechanistic codes can and have been used to integrate fission product transport and containment response into accident simulations.

SCDAP/RELAP5-3D© is composed of RELAP5, SCDAP, COUPLE, and MATPRO modules. RELAP5 is based on a two-fluid, non-equilibrium model for calculating RCS thermal-hydraulics, including flow through porous media. SCDAP contains models for predicting core damage progression, including fuel rod ballooning with corresponding changes in hydraulic flow paths, heatup and oxidation of fuel rods and related core components, fuel melting and in-core molten pool formation, and relocation of molten corium to the lower head accounting for interaction with the lower core support plate and other lower head structures. COUPLE provides a two-dimensional finite element framework for detailed simulation of any reactor area of interest, typically applied in predicting lower head response following corium relocation. MATPRO contains an extensive library of data and subroutines used to establish material properties and reaction rates in conjunction with reactor simulation.

SCDAP/RELAP5-3D© has complete flexibility that allows modeling individual components, separate subsystems, or an entire reactor complex with fully-integrated control system logic. Nodalization of the Westinghouse AP600 reactor including lower head details is shown in Figure1 as an example of a detailed model. The code flexibility arises from a combination of user-definable boundary conditions and a comprehensive set of user-selectable components (i.e., pipes, pumps, turbines, valves, accumulators, separators, fuel rods, control rods, control blades, core shrouds). The code is fully capable of simulating the effects of virtually any postulated reactor accident including (but not limited to) scenarios covering the complete range of potential break sizes (or loss of coolant accidents), station blackout events, anticipated transients without scram, reactivity insertion accidents, and secondary system faults (turbine trips, loss of feedwater, valve failures, etc.).

SCDAP/RELAP5-3D© evolved from the one-dimensional RELAP5 and SCDAP/RELAP5 codes developed at the Idaho National Engineering & Environmental Laboratory (INEEL) for the Nuclear Regulatory Commission (NRC). Development of the RELAP5 series began at INEEL in 1975 while SCDAP development was initiated in the early 1970’s with an integrated link to RELAP5 in 1979. Following the Chernobyl accident, the U.S. Department of Energy (DOE) began a re-assessment of the safety of their test and production reactors, and chose RELAP5 and SCDAP/RELAP5 as their safety analysis tools because the codes are broadly accepted and easy to apply to widely-varied systems. Application to various DOE reactors created the need for new modeling capabilities. Until recently, the INEEL maintained NRC and DOE versions of the codes in a single source that could be appropriately partitioned before compiling. However, the codes were ultimately ‘split’ into two versions, one for NRC and one for DOE. Current differences between the code versions are summarized in Table1 and highlighted in the balance of this paper.

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a. The SCDAP/RELAP5-3D© Code Development Team, *SCDAP/RELAP5-3D© Code Manual*, INEEL/EXT-02/00589, Idaho National Engineering and Environmental Laboratory, May2002 (http://www.inel.gov/relap5).

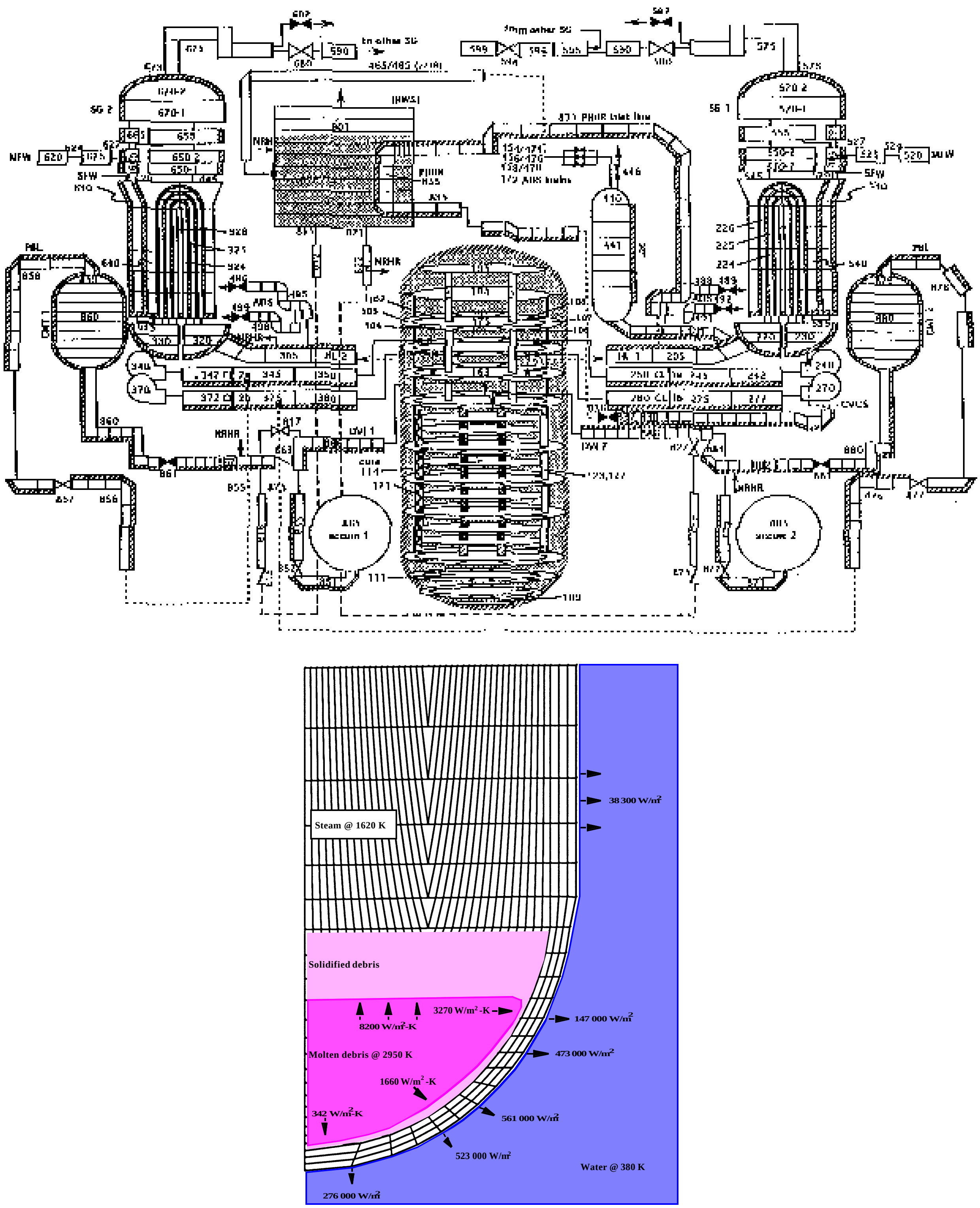

Figure 1. Nodalization of the Westinghouse AP600 reactor including details from the axisymmetric lower head model.

Table 1. Differences between SCDAP/RELAP5-3D© and SCDAP/RELAP5MOD3.3.

		SCDAP/RELAP5-3D©	SCDAP/RELAP5MOD3.3
Sponsor		U.S. DOE	NRC
Capabilities & Features	Multi-dimensional thermal-hydraulics	Yes	No
	Multi-dimensional kinetics	Yes	No
	(RELAP5) multi-dimensional heat transfer	Yes	No
	Advanced linear equation matrix solver	Yes	No
	MHD and non-aqueous fluids processing	Available[a]	No
	Corium/vessel gap heat transfer models	Yes	No
	(RELAP5) reflood models	Yes	Yes
	(SCDAP) refined nodalization for reflood or micro-heterogeneous fuels	Yes	No
	High burnup fuel and cladding properties	Yes	No
	Properties for alternate fuels (ThO_2/UO_2)	Yes	No
	Refined gap conductance models	Yes	No
	(SCDAP) automatic power profile generation	Yes	No
	Integrated links with COBRA, CONTAIN, and FLUENT CFD codes	Yes	No
	Executive program for linking other codes	Yes	No
	Interfaces with ABAQUS, FIDAP, PATRAN, and VICTORIA	Yes	No
	(RELAP5) simulator capable	Yes	No
	Direct access restart/plot file	Yes	No
	Graphical user interface	Input checking/interactive run-time control/result processing	RELAP5 input builder only
Support	Mode of development	Active	Maintenance only
	Official code releases	10 in last 5 years	None in last 5 years
	Unofficial releases	Dozens in last 5 years	4 in last 5 years
	Code development	Full	Limited RELAP5 only
	Analysis/modeling	Yes	RELAP5 only
	Training/workshops	Yes	RELAP5 only
	Problem reports resolved (2001)	60%	30%

a. Through the ATHENA version of the code.

Capabilities

The DOE version of the code (or SCDAP/RELAP5-3D©) retained all of the capabilities and validation history of the NRC predecessor code (or SCDAP/RELAP5MOD3.3), plus the added capabilities sponsored by the DOE before and after the split. Some of the most prominent attributes that distinguishes the DOE code from the NRC code are the fully integrated, multi-dimensional thermal-hydraulic and kinetic modeling capabilities in SCDAP/RELAP5-3D©.

Multi-dimensional capabilities were developed to allow more accurate modeling of the complex behavior that can be exhibited in reactors. The thermal-hydraulic component allows users to define a one, two, or three-dimensional array of volumes and associated internal junctions as appropriate. This model has been subjected to substantial testing and refinement. Results that typify the code capabilities are shown in Figure2, where computed flow patterns closely match those observed in the Rensselaer Polytechnic Institute (RPI) Test Section.

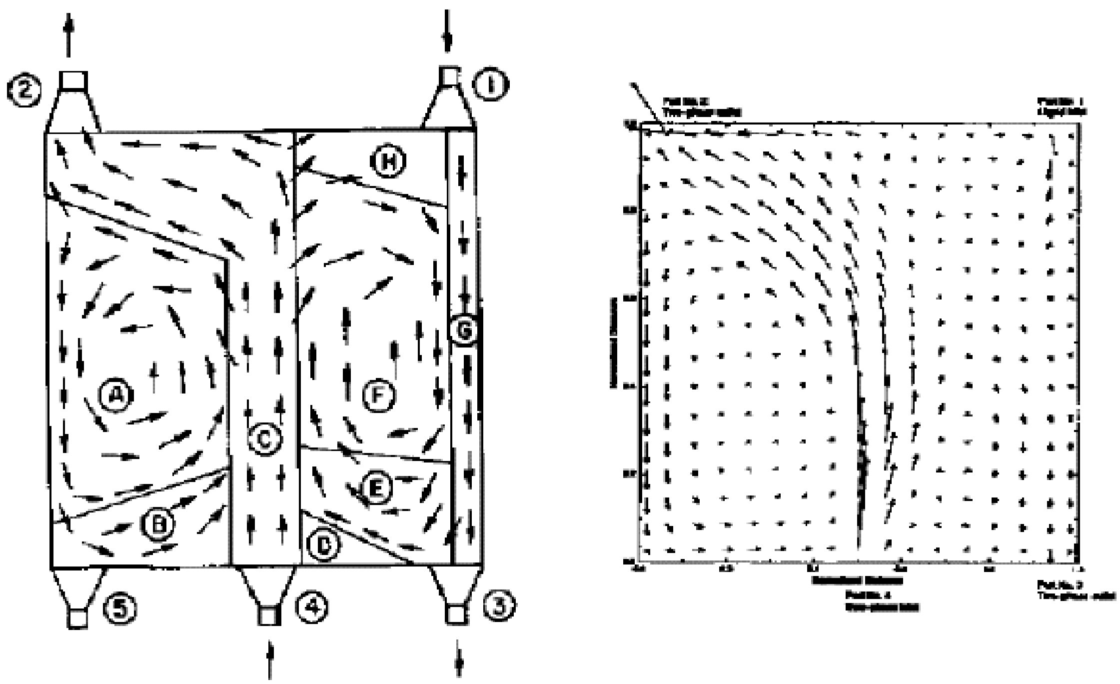

Figure 2. Observed and computed flow patterns in the RPI Test Section.

The multi-dimensional kinetics model in SCDAP/RELAP5-3D© is based on the NESTLE code developed at North Carolina State University under an INEEL initiative. The NESTLE code solves the two or four group neutron diffusion equations in either Cartesian or hexagonal geometry using the nodal expansion method and the non-linear iteration technique. One, two, or three-dimensional models may be used.

Structural heat transfer refinement is also part of the multi-dimensional code capabilities. This model allows connection of RELAP5-3D© structures to approximate multi-dimensional heat transfer as needed.

The Border Profiled Lower Upper (BPLU) matrix solver was developed to efficiently solve sparse linear systems. BPLU is designed to take advantage of pipelines, vector hardware, and shared-memory parallel architecture to reduce runtime. Speed-up by as much as a factor of 3.5 has been achieved running with BPLU over the default solver for simple 3D problems.

Heat transfer in corium-to-vessel gaps (if they develop following corium relocation to the lower head) is important because it affects the potential for in-vessel retention of corium and, therefore, the safety of the reactor. A typical gap configuration that can be simulated using SCDAP/RELAP5-3D© models is shown in Figure3. The models automatically invoke full logic thermal-hydraulics with countercurrent flow limitations in the gap, although this logic is currently based on correlations primarily developed for pipe flow. The potential benefit relative to vessel heatup is clearly shown in the figure.

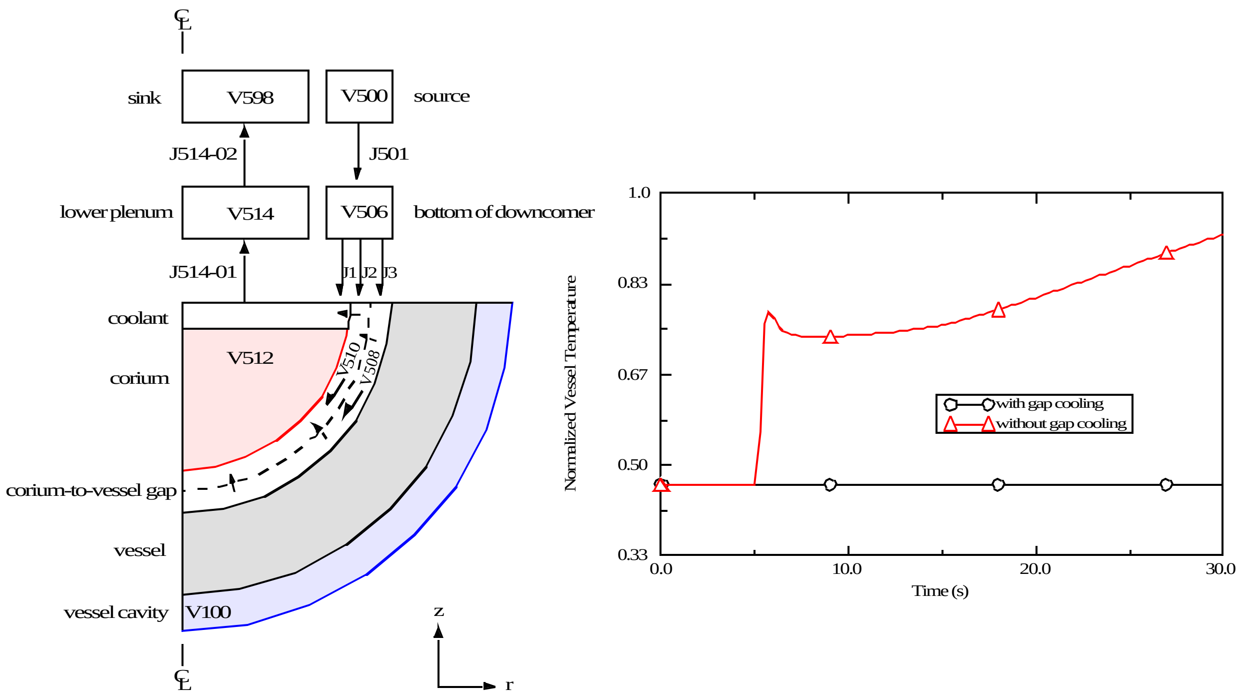

Figure 3. Typical corium-to-vessel gap nodalization (not to scale) and the effects of the gap on results.

Reflood models are included in both RELAP5 and SCDAP. These capabilities are essential for analyzing accident recovery strategies. Recently, a number of features have also been added to facilitate analysis of advanced and next generation reactor concepts. Fuel and cladding properties for high burnup operation, properties for alternate oxide fuels, refined gap conductance models, and the capability to automatically generate axial power profiles in SCDAP fuel rods are included in this group.

Fully-integrated links have been constructed to connect SCDAP/RELAP5-3D© with COBRA[a] (for detailed three-field analyses of continuous vapor, entrained liquid drops, and continuous liquid flows), CONTAIN[b] (for mechanistic analyses of reactor containment response), and FLUENT[c] (for analyses of complex flow fields). These links provide complete run-time feedback between the selected codes. The capability to develop similar links was significantly extended through recent development of an executive program based on the parallel virtual machine (PVM) message passing protocol. With this executive, addi-

a. C. Paik et al., *Analysis of FLECHT-SEASET 163 - Rod Blocked Bundle Data Using COBRA-TF*, NUREG/CR-4166, May1985.

b. K. K. Murata et. al., *Code Manual for CONTAIN2.0, A Computer Code for Nuclear Reactor Containment Analysis*, NUREG/CR-6533, December1997.

c. Fluent Inc., *FLUENT5 User's Guide*, July1998.

tional integrated links with any code of interest can be readily established. Coupled analyses, without run-time feedback, are also possible in cases where feedback may not be critical. ABAQUS[a] (for detailed structural analyses), FIDAP[b] (for widely-varied finite element simulation), PATRAN[c] (for finite element mesh generation and output processing), and VICTORIA[d] (for simulation of fission product transport) have all been used in this mode. An example of a coupled ABAQUS / PATRAN lower head analysis is shown in Figure 4.

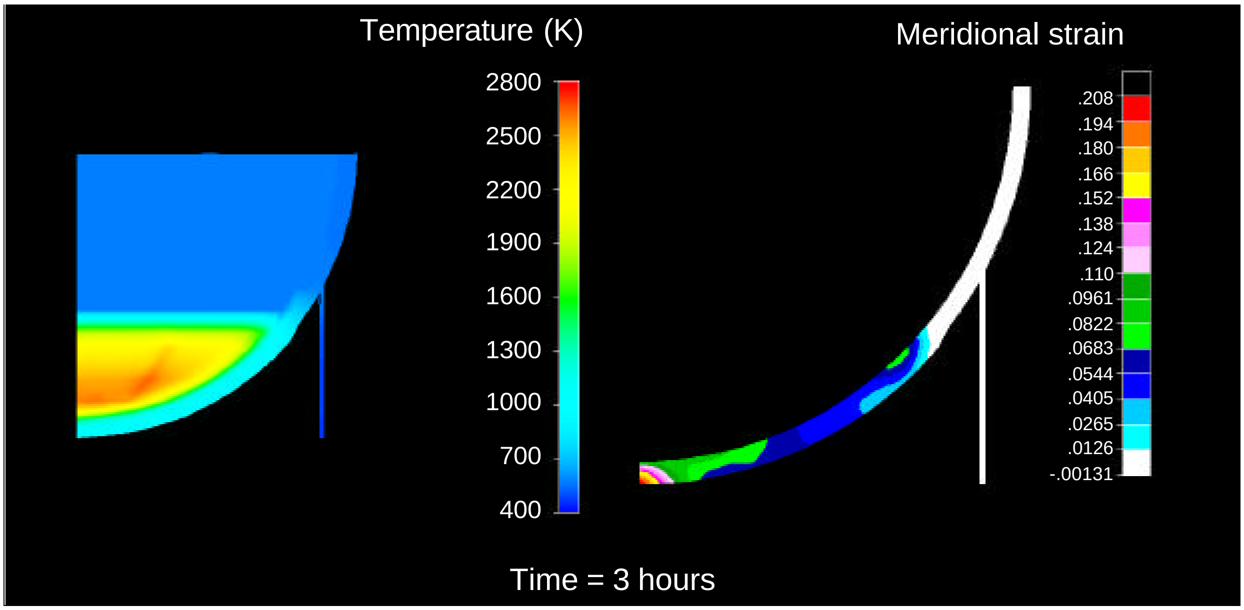

Figure 4. Coupled SCDAP/RELAP5-3D© / ABAQUS / PATRAN model for detailed structural analysis.

Versions of the code are available for application in operator training simulators. These versions rely on parallel processing capabilities using multiple CPU machines to achieve the necessary 'real time' performance. Direct access restart plot file capabilities are provided in all code configurations. This yields an additional efficiency for all users, particularly with respect to result processing.

A sophisticated graphical user interface (GUI) is also available for SCDAP/RELAP5-3D©. The GUI provides a very useful visual interface between the code and the user. This graphical interface is almost indispensable with respect to constructing and interpreting results from complex models. Some of the functions supplied by the GUI include a quick and easy visual mechanism for checking model input, interactive capabilities for direct execution of the code, extensive processing of results with static and dynamic plot capabilities as well as a number of different options for solid surface representation. The ability to observe the progression of a events during a transient often leads to a more accurate interpretation of plant behavior much faster than traditional reliance on simple xy plots. Typical GUI displays are shown in Figure 5 as an example.

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a. Hibbitt, Karlsson, & Sorenson, Inc., ABAQUS Version 6.2 Product Description, October 2001.

b. FLUENT Software Corp., *FIDAP,* http://www.fluent.com/software/fidap.

c. MSC Software Corp., *MSC.PATRAN,* http://www.mscsoftware.com.

d. N. E. Bixler, *VICTORIA2.0, A Mechanistic Model for Radionuclide Behavior in a Nuclear Reactor Coolant System Under Severe Accident Conditions,* NUREG/CR-6131, December1998.

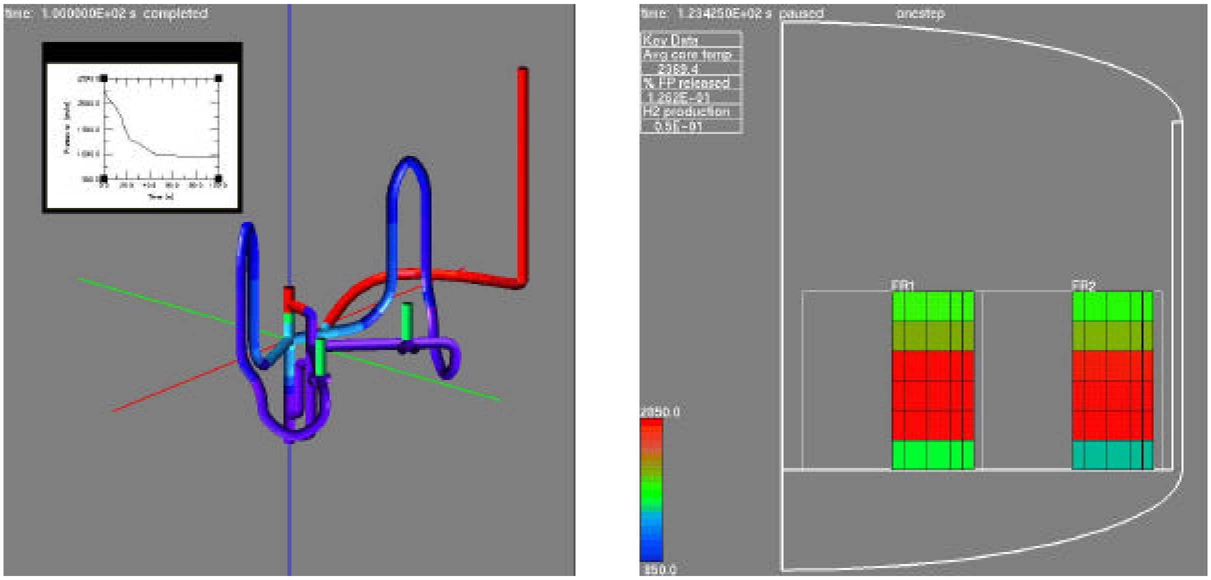

Figure 5. Typical GUI displays.

Support

As important as modeling advances embodied in SCDAP/RELAP5-3D© may be, it should be recognized that code technical support plays an equally important role. Without technical support, in both development and analysis activities, productive use of the code may be limited. Fortunately, SCDAP/RELAP5-3D© development teams are intact at INEEL and active development is in progress as clearly indicated by the numerous official and unofficial releases recently produced. Furthermore, INEEL can offer a full range of assistance with user training and modeling/analysis issues. The combination of advanced features, ongoing development, and full technical support make SCDAP/RELAP5-3D© an ideal choice for reactor accident analysis.

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